Biomechanics Parameters in Teenage Cyclist – SUV Accident and Comparison with the Pedestrian

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Abstract: - The study of the injury caused by the vehicle-teenage cyclist crash is presented in this paper. The vehicle is a SUV, with high frontal part, in order to compare the results with those obtained previously in the sedan- teenage cyclist crash and begin a study of the influence of the frontal shape of the vehicle. No variation is executed on the model of the teenage cyclist and the bike. Three different positions are analyzed: front, rear and lateral position. The injury on the cyclist head is examined by HIC criterion, in the way indicated in the rules. Correlation HIC – AIS is used to calculate the lethality of the injuries. The principal conclusion is done that the injury of the head is more dangerous for the SUV impact than the sedan, but only at the maximum speed (50 km/h). The injury to the chest is analyzed by 3 ms criterion; the injury is greater for the SUV impact than the sedan, but the entity is strongly dependent on the cyclist position. A comparison is executed with both the teenage and adult pedestrian concluding that the pedestrian is subjected to greater injury, because the bike absorbs a part of the energy in the front and side crash. The more dangerous injury is the telescoping. A further comparison show that the shape of the bonnet and the height of the frontal part have to be studied in an accurate way to reduce the injury to pedestrians and cyclists.

Key-Words: - teenage bicyclist, SUV impact, sedan impact, severe (AIS4+) injury, HIC**,**

1 Introduction

The energetic systems for the mobility in the automotive field are changed in the last years, like the beginning of this year 2015 highlighted.

In the field of Internal Combustion Engines, Diesel exceed petrol engines by almost double (55,2% against 31,1%); GPL, CNG, Hybrid and Electric occupy almost 14% of the domestic market (fig. 1).

The phenomenon of the Sport Utility Vehicle occupies 20% of the total sales, while in America this vehicle type has a greater spread (fig. 2).

In the last year one can count 136,438 accidents in Italy, with 184,683 casualty and 1,421 deaths of which 250 are cyclists (ANIA 2014).

Many works are found in literature on the impact between vehicle and teenager [1] [4] or adult pedestrian [2] [3] [5] [10] [19] [24] [29] [30], also numerous are the works that study the impact between the vehicle and the adult cyclist [9] [11] [13] [17] [18] [21] [22] or both cyclist and pedestrian [6] [7] [8] [12] [14] [23], but there was in literature a gap on the accident vehicle - teenage cyclist [15] [16] [20]; other works are not found on this scope.

In general multibody numerical simulation is the applied method; the most widely used programs are MADYMO, Aprosys, PC Crash, while the Authors effectively use Visual Nastran 4D.

Studies give an idea of the shape of the front of the vehicle in order to reduce injuries, that may arise due to collision [19] [30], but these works are not frequent in literature. In particular the works [22]

[23] [24] also address the crash between SUV vehicle against cyclist or pedestrian.

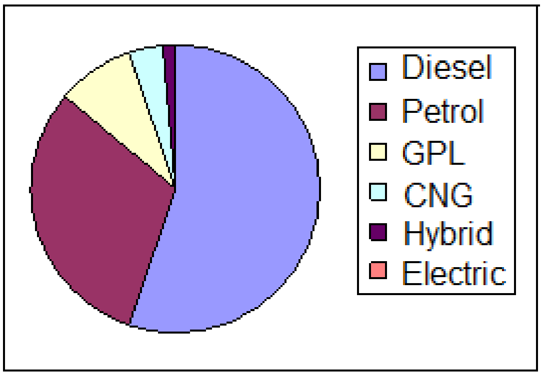

Fig. 1: Italian market for feeding (UNRAE April 2015).

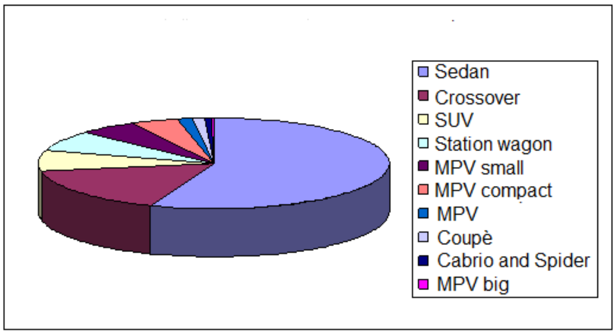

Fig. 2: Italian market for bodywork (UNRAE April 2015).

This paper extends the results already achieved in the works [15] [16] where the damages caused by the energy impact of a teenage cyclist with a sedan car are taken into account and analyzed. Analogous crash is studied in case of vehicle constituted by a SUV instead than a normal sedan, in order to fill the gap in literature: reference is made only to an adult or a child without taking into account the type of vehicle.
A campaign of virtual simulations is conducted with the availability of the virtual model SUV-teenage cyclist, in order to quantify the damage caused to the head and chest on the basis of certain criteria such as HIC and 3 ms criterion [15] [16] [25] [26].

2. Implementation of Virtual Models

The paper [1] is very useful for the study of anthropomorphic model of the human figure of a teenager, understood as a complex of bones, muscles and joints, while the paper [3] has analogous value for the adult; the book [27] and the paper [28] are very useful for the chassis design and the geometry of the bike

Virtual simulations, performed with Visual Nastran, allowed to quantify the damages in the teenager cyclist – SUV impact on head and chest. Specifically HIC criterion is used regard to head injuries. The dynamics taken into consideration concerns the crash front, side and telescoping.
Difficulties encountered in the study are numerous: CAD implementation of wheels, seat, chassis bonnet and front bumper of the SUV, the geometry of the frame, the vertical position of the center of gravity and the study of the stability of the bicycle.
Instead the implementation of the joints of the human figure, the model of the cyclist and the bike are those already adopted in the works [15] [16]; then the further focus on this topic is not considered appropriate.
The car chosen for the simulations is the SUV Mercedes class M. Information on wheelbase, height, length is provided by the manufacturer.
This type of SUV is chosen for its characteristics: larger structure, monoshell bodywork, the more aggressive mask, and the great mass.
CAD model is obtained by Sketchup software, the model is later imported into Visual-Nastran, inserting the masses, centers of gravity and the inertia moments of the individual components such as wheels, body, chassis, bonnet, front bumper. These parameters are essential for the proper conduct of the simulations and the acquisition of results (Fig. 3).

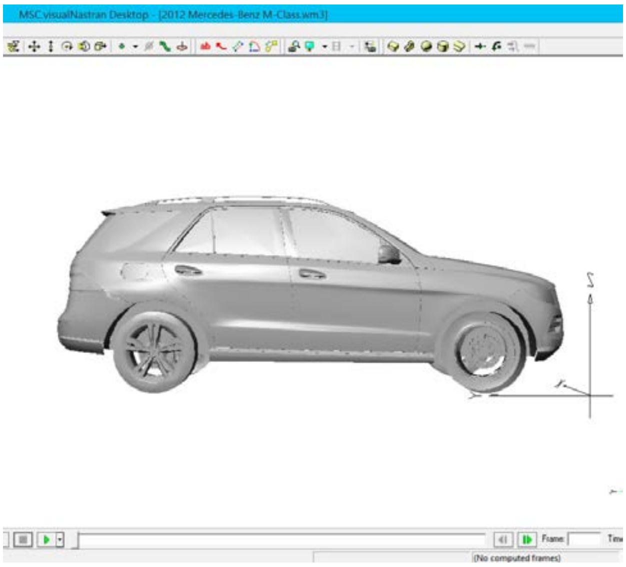

Fig. 3: SUV in Visual Nastran

3. SUV - Cyclist Accident

Visual Nastran allows the reconstruction of the main conditions constituting the dynamic of a teenage cyclist - SUV crash.

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In the general case teenage cyclist is placed in a perpendicular position to the longitudinal axis of the road, and goes on the direction perpendicular to the oncoming vehicle at negligible rate. The actions of the vehicle driver has a decisive role in the evolution of the accident.
The most common attitude of the drives is the deceleration by instinct, in order to reduce the consequences of the impact, but it remains to be seen whether the braking of SUV resolves positively or less the accident evolution.
Speed reduction can only cause minor injuries on the cyclist with respect to a constant speed; but despite the perception and reaction times of the driver, the real decrease of SUV speed is often very poor: although the SUV has a braking capacity to impose an average deceleration greater than 0.6g, the effectiveness of braking action is achieved near the instant of impact in most cases.
The teenage cyclist is found in the same three positions examined in the papers [15] [16]. In the first case he is stopped on the roadway with the side facing the overcoming SUV (side impact).
In the second case the cyclist is located in front of the overcoming SUV (front impact), while in the third and last case the SUV is placed behind the cyclist (rear impact or telescoping).

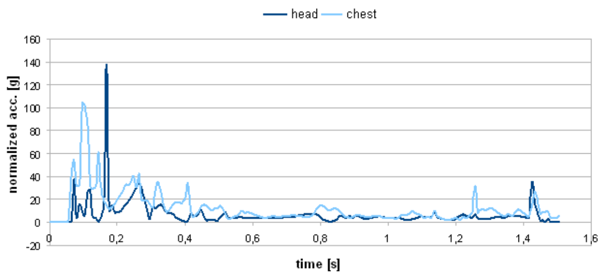

Fig. 4: Head and chest acceleration in the frontal impact at 50 km/h

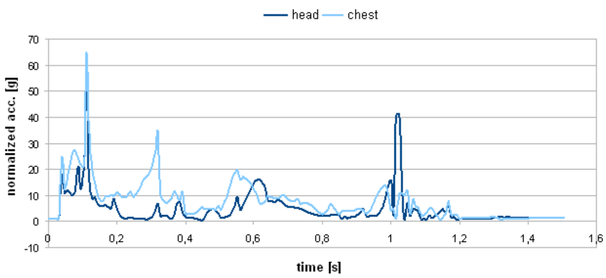

Fig. 5: Head and chest acceleration in the side impact at 30 km/h

The constraint of Visual Nastran 4D, named "rope", allows that the rider remains upright until an instant before the impact occurs with the SUV.

Since the Highway Code sets the maximum speed of 50 km/h in the urban land, also the crash tests meet this limit. Whereas a speed of 50 km/h can be fatal in the event of impact, crash tests are performed even at the speed of 20 km/h, 30 km/h and 40 km/h for a better study of the problem.

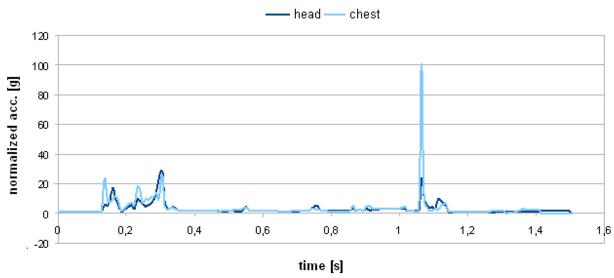

Fig. 6: Head and chest acceleration in the telescoping at 20 km/h

3.1 Numerical Simulation

Measured parameters during the simulations are:
- acceleration of the head gravity center;
- acceleration of the chest gravity center.

Fig. 4, fig. 5 and fig. 6 show the trend of the head and chest acceleration, versus the time for some significant test.

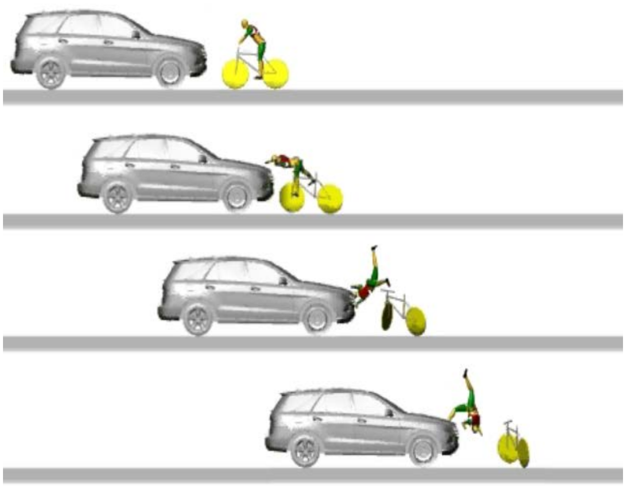

Fig. 7: frontal impact at 50km/h, constant speed.

Events reconstruction in Visual Nastran allows observing the trajectory taken by the teenage cyclist throughout the collision, by comparing each time the data extracted from the simulation with the frames of the test.

The sequences represented in fig. 7 and fig. 8 show the different trajectories of the teenage cyclist in function of the different simulation conditions.
Fig. 7 illustrates the dynamic of the frontal impact at 50 km/h; the thrust of the front bumper and the forward projection of the cyclist may be noted.
Fig. 8 depicts the cyclist trajectory in the side impact: the cyclist is invested laterally by the oncoming vehicle at a constant speed of 50 km/h. The thrust forward and the wheeling of the cyclist body may be noted.

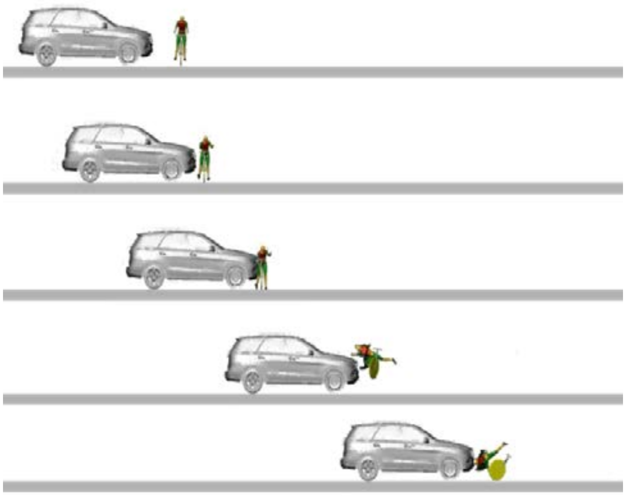

Fig. 8: lateral impact at 50km/h, constant speed.

Table 1: synthesis of the obtained values and HIC.

Test	Position	Vel. [km/h]	$A_{max\ head}$ [g]	HIC
1	Frontal	20	58,51	239,51
2	Frontal	30	67,86	310,16
3	Frontal	40	90,13	569,38
4	Frontal	50	137,84	1453,44
5	Lateral	20	13,52	10,47
6	Lateral	30	54,31	190,30
7	Lateral	40	88,61	565,29
8	Lateral	50	127,51	1317,17
9	Rear	20	28,59	46,80
10	Rear	30	48,68	181,97
11	Rear	40	106,18	823,01
12	Rear	50	154,77	3055,83

3.1.1 Test analysis and HIC calculation

Simulations give very useful information for the analysis of the crash effects. Table 1 shows the synthesis of the obtained results in terms of head acceleration and the relative values of HIC. This calculation is executed following the rule, by the traditional formula, assuming a base of time equal to 36 ms; fig. 9 shows the trend.

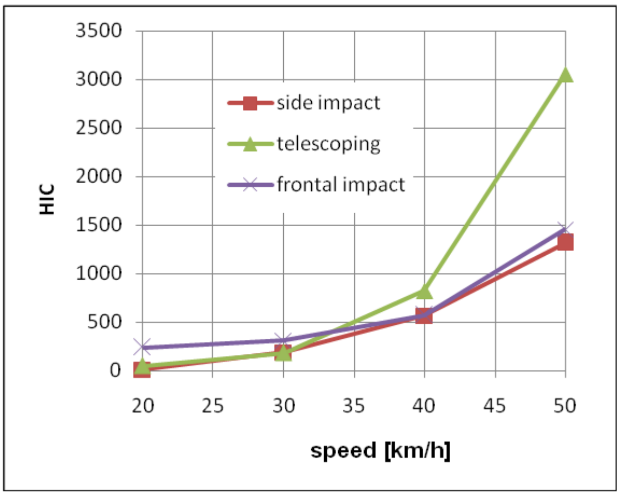

Fig. 9: HIC versus the impact speed.

3.1.2 HIC-AIS correlation

Table 2 shows the correlation HIC-AIS. HIC data, obtained by the simulations with the injury scale AIS, give the lethality percentage of the event. Fig. 10 shows the procedure: HIC value is reported in the abscissa and the ordinate gives the corresponding percentage of lethality.
The lethality curve of fig. 10 is obtained in previous works i. e. [1] [2] and relative references.

Table 2: lethality percentage by HIC – AIS correlation

Test	Position	Vel. [km/h]	AIS	% lethality
1	Frontal	20	1	0
2	Frontal	30	1	0
3	Frontal	40	2	10-20
4	Frontal	50	4	50-60
5	Lateral	20	1	0
6	Lateral	30	1	0-5
7	Lateral	40	2	10-20
8	Lateral	50	4	50-60
9	Rear	20	1	0
10	Rear	30	1	0
11	Rear	40	2	10-20
12	Rear	50	6	100

3.2 Considerations on the Results

The simulations are distinguishes in three groups:

1. simulations 1-4 for frontal impact
2. simulations 5-8 for side impacts
3. simulations 9-12 for rear impact.

Fig 5 shows that side crash sees a series of peaks of acceleration caused by the impact on the lateral plane of the skull against the front of the SUV (bumper and bonnet); in these cases the first contact

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with the bonnet occurs by the shoulder and, at a later time, with the head. These peaks are repeated generally in the short round of 0.01s due to some rapid rotation of the head around the joint of the cervical neck.

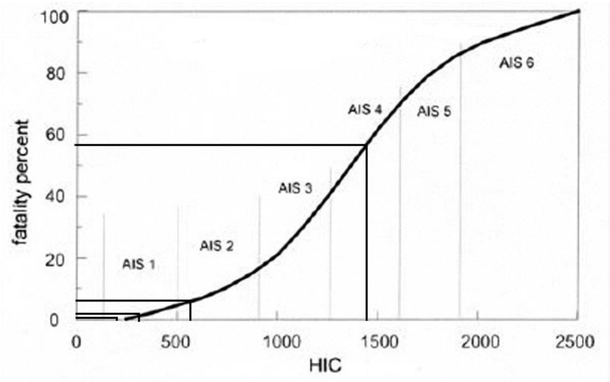

Fig. 10: HIC-AIS correlation (frontal impact at constant speed)

Both front and rear impacts trends are very different one another at different speed. The head, because of the first contact of the teenage cyclist with the bumper of the vehicle, is strongly projected backwards. So that the center of instantaneous rotation of the cervical varies, by determining a variation of the moment of momentum which results in a substantial increase of the angular acceleration of the whole head. In some cases, there is an overlapping between the impact of the head and the contact of the chest on the bonnet; this gives a considerable increase of the measured accelerations for the chest.

Table 3: comparison of HIC for SUV and sedan

test	Position	Vel. [km/h]	Difference with sedan HIC
1	Frontal	20	+1904%
2	Frontal	30	+2240,9%
3	Frontal	40	+2101,8%
4	Frontal	50	+277,6%
5	Lateral	20	-69,9%
6	Lateral	30	-63,5%
7	Lateral	40	-7%
8	Lateral	50	+104,5%
9	Rear	20	-53,3%
10	Rear	30	-42,5%
11	Rear	40	+139,1%
12	Rear	50	+512,2%

3.2.1 Comparison SUV - sedan

Table 3 shows the difference in percent between the analysis of the impact sedan – teenage cyclist, obtained in [15] [16] [20], and SUV- teenage cyclist, in terms of HIC.

Fig. 11, fig. 12 and fig. 13 show the trend and the visual comparison.

The teenage cyclist has lower chance to survive in the front, side and rear impact with the SUV, in the range of speed 40-50 km/h, because HIC values are consistently greater than the survival values, obtained as in fig. 10.

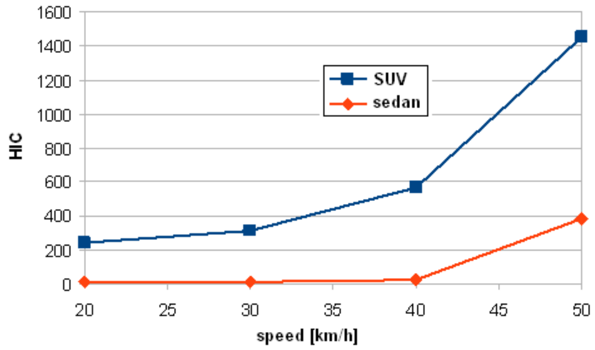

Fig. 3: comparison SUV – sedan for HIC in the frontal impact.

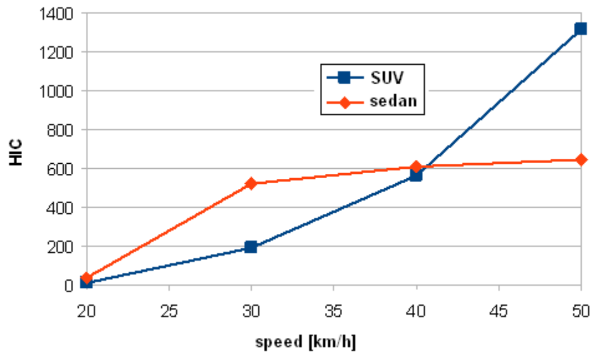

Fig. 12: comparison SUV – sedan for HIC in the lateral impact.

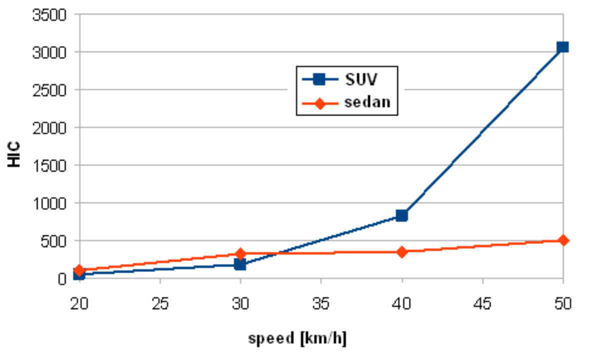

Fig. 13: comparison SUV – sedan for HIC in the telescoping.

3.2.2 Comparison with other results

Impact simulations SUV - teenage pedestrian are executed in [24], by the multibody software MADYMO. The teenager is in frontal/rear position regard to SUV; no distinction is made between frontal or rear position, so that fig. 14 shows the comparison with Visual Nastran 4D results of the rear position only, given that the difference with the frontal position is very small. Fig. 15 shoes the analogous comparison for the lateral position; the fact that the comparison is between teenage pedestrian (MADYMO) and teenage cyclist (VN 4D) has to be remarked.

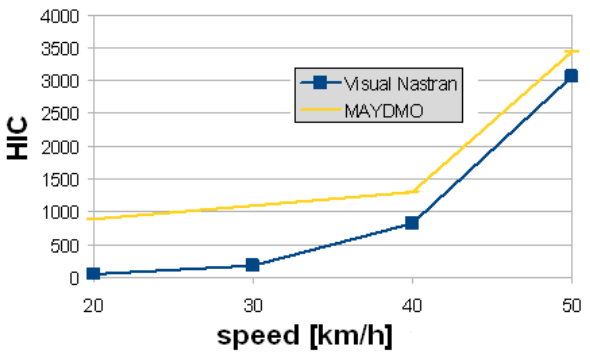

Fig. 14: comparison HIC for frontal/rear simulations in Visual Nastran and MAYDMO environments.

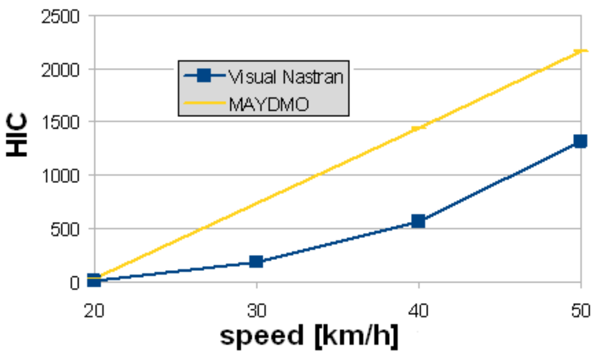

Fig. 15: comparison HIC for lateral simulations in Visual Nastran and MAYDMO environments.

This comparison allows some considerations:
- Front/rear and side simulations show that teenage cyclist has a greater chance to survive regard to a teenage pedestrian, as the HIC values are consistently below the survival values;
- Part of the impact energy is absorbed by the chassis of the bike with the same impact velocity SUV – teenage pedestrian in the front and side simulations.

3.2.2.1 Comparison with adult pedestrian

A comparison is possible with some data in [32] [33]; the papers contain impact tests vehicle – adult pedestrian, implemented by the use of MAYDMO and SIMPACK multibody programs. Pedestrian is found in side position regard to vehicle. Fig. 16 shows the trend and the comparison.

This comparison allows further considerations:
- Teenage cyclist has greater possibility of survival to the side impact than the adult pedestrian, since HIC values keep under the values of adult pedestrian. The data obtained in [2] are confirmed.
- Part of the crash Energy is absorbed by the bike chassis-
- HIC trend versus the speed is always increasing with the speed. The same event is not repeated in the other simulations [32] [33].
- The obtained data highlight that the speed 20 km/h is the speed of lower injury, while the critical value happens at 50 km/h.

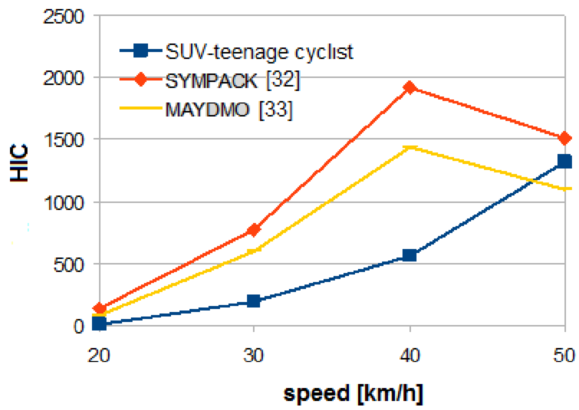

Fig. 16: Comparison with HIC adult pedestrian (MAYDMO,SIMPACK).

3.3 Chest Injury evaluation by 3ms criterion

Evaluation of the chest injury is executed by 3 ms criterion. It provides that the both chest and head gravity centers do not suffer greater accelerations than 60g and 80g respectively, for a time greater than 3ms. A virtual accelerometer is inserted in the chest gravity center to obtain the wanted results; they are shown in table 4.

Table 4: Values by 3ms criterion

Test	Position	speed [km/h]	3ms [g]
1	Frontal	20	75
2	Frontal	30	117
3	Frontal	40	160
4	Frontal	50	180
5	Lateral	20	17
6	Lateral	30	64
7	Lateral	40	58
8	Lateral	50	150
9	rear	20	24
10	rear	30	83
11	rear	40	334
12	rear	50	370

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Fig. 17 shows the trend of the obtained values using 3ms criterion versus the impact speed of the simulation.
The injury probability AIS4+ (thorax fracture and aorta laceration) is obtained by the relationship:

$$AIS4+ = 1 / (1+exp\ (4{,}3425-0{,}0630 * g_t)) \qquad (1)$$

Where g_t is the acceleration calculated by 3ms criterion. Results are shown in table 5.

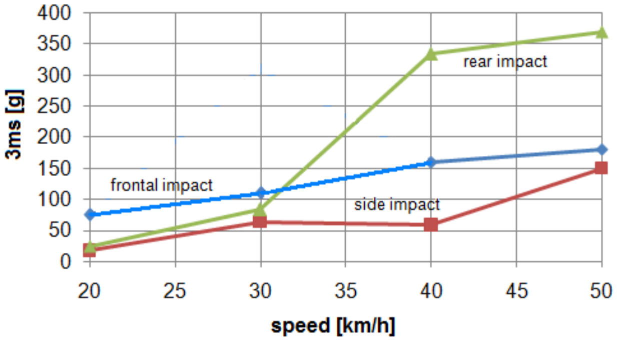

Fig. 17: trend of the values by 3ms criterion

Table 5: probability of injury AIS 4+

Test	Position	speed [km/h]	AIS 4+ [%]
1	Frontal	20	59,4
2	Frontal	30	95.4
3	Frontal	40	99.7
4	Frontal	50	99.9
5	Lateral	20	3.6
6	Lateral	30	42.3
7	Lateral	40	33.4
8	Lateral	50	99.4
9	Rear	20	5,6
10	Rear	30	70.8
11	Rear	40	100.0
12	Rear	50	100.0

One can ascertain that acceleration values suffered by the thorax are very high at speeds 40 and 50 km/h. It is due to the trunk ability to bend at direct contact of the thorax with the SUV.

3.3.1 - 3ms criterion results comparison

Table 6 shows the difference in percent between the results obtained by the SUV-cyclist simulations and sedan-cyclist. Of course the data are obtained by 3 ms criterion for a comparison; the sedan-cyclist data are reported in the papers [15] and [16]. Graphic comparison is shown in Fig. 18 – 20.
In the case of side impact, at moderate speed, SUV impact is more dangerous than the sedan impact for the teenage cyclist, especially if the chest hits against the windscreen, that is the more rigid part of the vehicle front. Instead the contrary occurs at high speed: the sedan impact is more dangerous than the SUV impact, in both the cases of frontal impact and telescoping, while the contact with the SUV is more dangerous in the case of side impact.

Table 6: comparison of the data by 3ms criterion between SUV cyclist and sedan cyclist impact.

test	Position	Speed [km/h]	Difference with sedan[%]
			3ms
1	Frontal	20	-40
2	Frontal	30	1.7
3	Frontal	40	10.3
4	Frontal	50	-20
5	Lateral	20	-45.2
6	Lateral	30	128.6
7	Lateral	40	0
8	Lateral	50	163.1
9	Rear	20	9.1
10	Rear	30	-9.8
11	Rear	40	33.6
12	Rear	50	-34.5

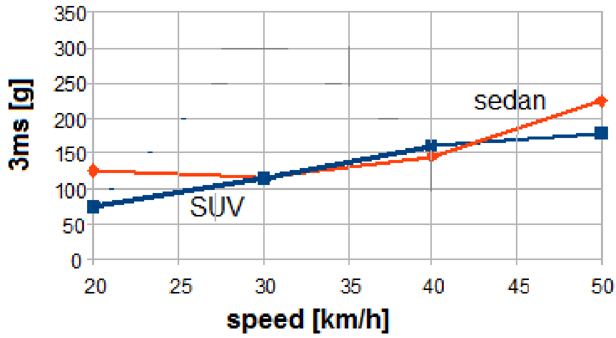

Fig. 18: 3ms criterion; comparison with the data of sedan-cyclist frontal impact.

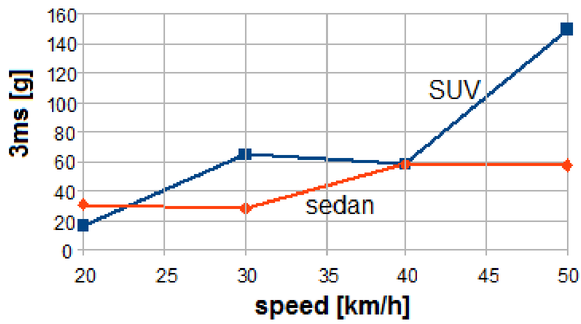

Fig. 19: 3ms criterion; comparison with the data of sedan-cyclist side impact.

The teenage cyclist has greater probability to suffer a chest injury in both frontal and rear impact with the sedan, since the values obtained by 3ms criterion keep higher.

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Differently the SUV generates greater injury to the chest of the cyclist in the side impact, due to the greater size and the height from the ground.
The shape of the frontal part of the vehicle has great importance for the injuries that may be generates in the subject; this vehicle part has to be studied accurately in order to minimize the accidents effect.

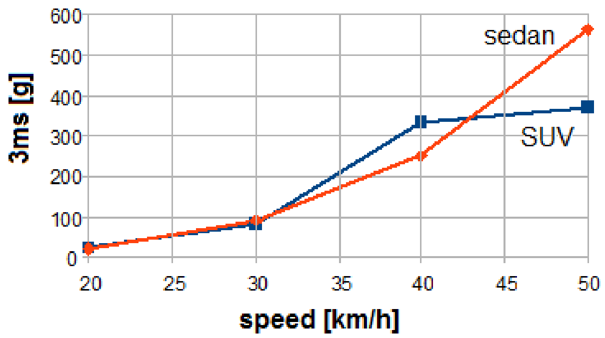

Fig. 20: 3ms criterion; comparison with the data of sedan-cyclist rear impact.

3.3.2 – Comparison of the chest injury in the frontal impact with 3ms criterion.

Table 7 shows the difference in percent between the impact analysis SUV – cyclist and vehicle – teenager, in term of the values obtained by 3ms criterion.

Table 7: Comparison of the results by 3ms criterion

test	Posit.	Impact speed [km/h]	Difference with teenage pedestrian [%]
			3ms
1	Frontal	20	+88,92%
2	Frontal	30	+87,50%
3	Frontal	40	+20,21%
4	Frontal	50	+33,53%

Fig. 21 shows the trend and the comparison. In the frontal impact a teenage pedestrian has always less likely to suffer injury to the chest than the same age cyclist, because values in [1] obtained by 3ms criterion are consistently lower.

3.4 Impact points location

Fig. 22 shows the points of the SUV bonnet where the subject hits the head during the impact. The marking of the vehicle for identifying the areas (WAD) is done according to the directives EURONCAP.

Impact point dispersion is localized in all cases in the area of the WAD 1500 except for impacts at 20 km/h (WAD 1000). The dispersion of the points in the case of rear impact involves a larger area than the other cases. Furthermore, the analysis of the contact points allows obtaining a new confirmation of the accuracy of the values. The acceleration peaks, even very intense, generally are due to a collision against a rigid wall of the vehicle front.

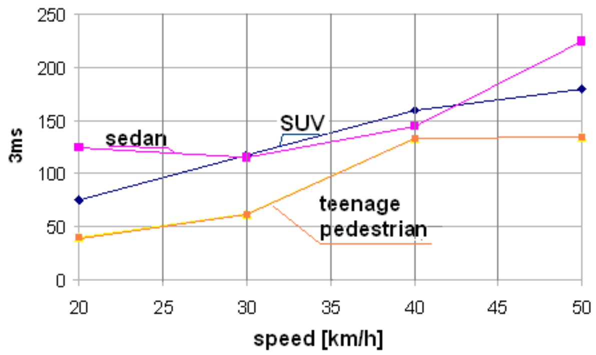

Fig. 21: comparison 3ms rear impact SUV – sedan cyclist and sedan – teenage pedestrian.

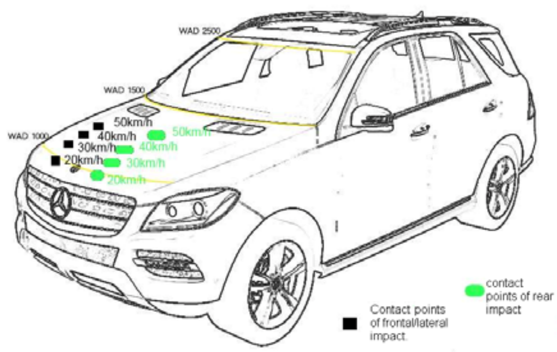

Fig. 22: Contact points head-SUV in the frontal, rear and lateral impact.

3.4.1 WAD comparison with the results of other Authors.

Paper [30] shows the sedan – pedestrian impact, by FEM. The pedestrian is found in side position regard to the sedan in the analyzed tests. The simulations are executed by the head form impactor following EURONCAP rules. The head form test considers the human body Wrap Around Distance (WAD) in order to define two different areas on the bonnet surface, where the head of a child (1000 - 1700 mm) or of an adult (1700 – 2100 mm) will hit. In this paper only the results of child impactor are used for the comparison.
The position of the contact points in [30] is put in relation with the contact points in fig. 22 to obtain the speed corresponding to the child impact (WAD

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being equal). Fig. 23 shows the trend and the comparison with the same WAD.

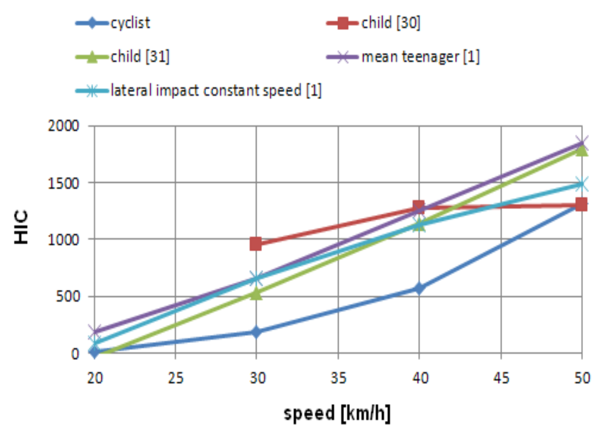

Fig. 23: comparison WAD side impact SUV - teenager.

In the same graph the results of the paper [1] for the teenage pedestrian are reported, both the mean value of the several impacts type, and the results for lateral impact at constant speed.
HIC values can be compared with those obtained by other authors. In particular 188 pedestrian accidents, selected by several database, are studied in [31]; the accidents are reconstructed by MADYMO. Authors distinguish between adults and children, without taking into account other factors such as compliance and the shape of the bonnet, the relative position, the pedestrian speed etc., by relating the value of HIC with the impact velocity. These results are statistically interpolated by curves of the second order. Equation for children is:

$$HIC = 0{,}2169v^2 + 46{,}141v - 1046{,}2 \qquad (2)$$
$$R^2 = 0{,}974$$

the independent variable v is the impact speed in km/h. The curves are shown in Fig. 23; the children show a lower value of HIC. In [31] “Child” is an individual having lower age than the teenager (less than thirteen years).
A number of considerations can be done by this comparison:
- The teenage cyclist has a greater chance of surviving than a pedestrian of the same age, in the impact side, because, at the same points of WAD analyzed in the impact, HIC values are consistently lower than the pedestrian;
- Part of the energy of impact is absorbed by the frame of the bike with the same points of WAD.
- 50 km/h speed is critical since it causes injury to teenage pedestrians and cyclists with the same entity.
- The values reported in [30] are a few in disagreement with the others for the speeds 30 and 50 km/h. This is due to the non-multibody software that is used in the simulations, and to the fact that the data are obtained using only the impactor form.

4 Conclusions

The aim of this work is not only to assess the damage caused in the event of accident, by analyzing the impact dynamic between SUV and bike, but above all, the aim is to try and suggest possible improvements and solutions to increase the safety and limit the damage by the weaker person.
Simulations, and the results comparison with other analysis, show the importance of certain key elements such as: the height of the rider, the front profile of the SUV, the ground clearance, and the rigidity of the parts that come in contact with the cyclist at the moment of impact.
Simulations show like the position of the cyclist at the time of the accident can affect the outcome of the impact: telescoping is more dangerous than the frontal impact; in fact HIC values obtained from simulations are higher than the frontal impact, because the head of the cyclist hits immediately the bonnet of the SUV. It overwhelms the cyclist, so that the bike does not absorb the shock, unlike what happens in the other cases.
Different thing happens in the frontal and side impact. In these cases SUV affects primarily the bike that absorbs the shock. Impact point is highlighted in the vicinity of the wheel and the cyclist falls in a different way, since he is located at a few greater distance (seemingly irrelevant).
In all the simulations, HIC values are lower than 1000 (limit imposed by the rules); this is possible because a good part of the impact is absorbed by the bicycle and not by the body of the cyclist. The speed of 50 km/h can be considered critical, given that HIC assumes very high values.
However the principal result of this paper is that the front shape of the vehicle has great importance to limit the injury to the cyclist or to the pedestrian that is the more weak part in the impact.
The values obtained by the simulations are almost all greater than the limit imposed by the regulation (60g), they are higher than the values obtained by the comparison with the pedestrian and with a higher parameter AIS+4 (thorax fracture and aorta laceration). The reason is the position of the cyclist gravity center that is higher than the pedestrian one; the chest hits the more rigid zones of the SUV in the impact instant.

The use of multibody virtual method for the simulations is beneficial, given that it implements numerous adaptations, especially if one considers that the prototypes existed only as CAD drawings. In this way, the study of SUV, which must necessarily pass imposed tests of approval, is certainly easier and can lead to reliable results, reducing also the excessive costs.

This kind of simulation has not only an impact on costs, but also on the safety, thanks to tests of the effectiveness of passive and active devices for a better performance.

Deformable bumpers improve the protection of the cyclist because they mitigates the violence of the impact on the legs; protection increases if the shock is applied to the lower part of the leg, away from the knee, and if the crash forces are spread over a greater length of the leg. It occurs in the lateral crash.

Front edge of the bonnet can be improved by eliminating all the unnecessary rigid structures. Finally, the ability of the bonnet to rise during the crash improves the protection of the cyclist (or pedestrian) head; this can be implemented by leaving greater space between the bonnet and the engine block.

It is necessary to make tests in order to understand better the influence of the bonnet interior panel. The analytical tests made in order to estimate the behaviour of the bonnet are useful in the design phase, when is possible to establish the best architecture of the panels which offer the best protection of the pedestrians or cyclist (adult or teenager).

Finally, making use of proximity sensors, the presence of a cyclist on the trajectory of the vehicle can be determined more effectively and rapidly in communicating the data to a control unit that provides to implement a braking in closer times than those obtainable from human reflexes, in order to reduce more effectively the speed at the instant of the crash.

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